Renewable and Sustainable Energy Reviews 26 (2013) 34–41

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Modeling of renewable energy resources for generation reliability evaluation

Kunjana Chaiamarit, Somboon Nuchprayoon*

Department of Electrical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand

ARTICLE INFO

Article history:
Received 25 December 2012
Received in revised form
17 May 2013
Accepted 20 May 2013
Available online 14 June 2013

Keywords:
Effective load carrying capability
Generation reliability
Loss of load probability
Renewable energy

ABSTRACT

The modeling of various renewable energy resources is proposed by considering daily operation profile. The forced outage rate of renewable unit can be obtained by using the equivalent forced outage rate. Generation reliability is then evaluated under the presence of renewable energy resources. The loss of load probability and the effective load carrying capability are used as reliability index and capacity contribution on reliability, respectively. A test system is built by scaling down the existing generation portfolio of Thailand. Numerical results are then provided and discussed under various loading conditions and penetration levels of renewable energy resources.

Contents

1. Introduction

Electricity generation from renewable energy resources has been increasing worldwide in accordance with concerns on energy problems (e.g. supply shortages, price spikes) and environmental impacts. The integration of renewable energy generation is considered as a solution for fuel independence and emission reduction.

* Corresponding author. Tel.: +66 5394 4135x304; fax :+66 5322 1485.
E-mail address: sn@eng.cmu.ac.th (S. Nuchprayoon).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.05.052

It is undeniable that renewable energy is on the rise. However, renewable energy technologies are not technically and economically competitive with conventional technologies. Given that costs of electricity generation from renewable resources are not competitive, supporting mechanisms by means of feed-in tariff, quota, auction, or incentive have been implemented to promote renewable energy [1]. Besides, some renewable energy resources (such as wind and solar) have low energy generation compared with much larger installed capacity. Thus, there is a requirement for additional generation and network capacities to accommodate renewable generation.

Thailand is also enthusiastic for renewable energy. The promotion of renewable electricity generation in Thailand has been driven by both financial incentive (called price adder) and feed-in tariff schemes. In addition, the renewable policy goals have been addressed by the Thai Government as shown in Table 1 in terms of the Power Development Plan (2010) [2] and the Alternatives Energy Development Plan (2008–2022) [3]. Electricity generation from renewable energy sources is aimed to be 20% of total energy consumption by 2022 [2].

One of the interested topics is how the penetration of renewable energy sources affects generation reliability [4–8]. This topic deserves more attention and becomes crucial as higher penetration of renewable generation is foreseeable. The initial assessment is that they would have adverse effect so that the provision of generation reserve is necessary for maintaining reliability of electricity supply.

The stochastic and intermittent characteristics of renewable energy resources should be considered and properly modeled for the assessment of supply adequacy and reliability. Given uncertainties associated with renewable energy resources, the risk of insufficient generation capacity might increase. Thus, higher amount of capacity reserves may be required to satisfy reliability criteria. It should be emphasized that when renewable energy resources are added into generation system without removing existing (fossil-fueled) plants, the generation reliability would even be better off and there is no point to be concerned. But, when renewable energy resources replace existing resources, generation reliability is of concern, especially in case of high penetration of renewable energy resources.

Hence, in this work, the modeling of renewable energy resources is proposed for evaluating generation reliability. The resources of interest are wind, solar, small hydro, biomass, and biogas; given that they have considerable potential for electricity generation in Thailand. The renewable generation models are described in Section 2. Generation reliability evaluation methods for conventional resources are reviewed in Section 3 and then applied to evaluate renewable energy resources in Section 4. The generation models of renewable energy resources and their impact on generation reliability are tested with a small-scale system and reported in Section 5. Finally, this work is concluded in Section 6.

Table 1
Renewable energy generation targets for Thailand in 15-year period (unit: MW) [3].

Resource	2008–2011	2012–2016	2017–2022
Solar	55	95	500
Wind	115	375	800
Small hydro	165	281	324
Biomass	2800	3220	3700
Biogas	60	90	120
Municipal solid waste	78	130	160
Hydrogen	–	–	4
Total	3273	4191	5608

2. Modeling of renewable energy resources

Thailand has various renewable energy resources including wind, solar, small hydro, biomass, and biogas. Given that the average wind speed in Thailand is relatively low [9], the potential of wind generation is limited to the areas along the coastlines and high mountains. The potential of solar thermal and photovoltaic generation are country wide. The limitations are investment costs and siting area. The potential of hydro generation is in terms of run-of-river, small-scale hydropower plants and mostly in the Northern region of Thailand. Note that, in case of small hydro and wind, environmental impact is another barrier because potential sites are mostly in the forestry. Biomass is the primary renewable source of electricity generation based on the fact that Thailand has high potential on agricultural stocks. Biomass is referred to products, residues, and wastes from agriculture and forestry. In Thailand, agricultural residues in use are rice husk and straw, bagasse, corn, palm, cassava, and wood chips [9,10]. Nonetheless, the absence of supply chain management and technological development are barrier for biomass generation. Biogas generation in Thailand is mostly from anaerobic digestion of organic wastes [11]. Thailand has developed biogas generation for over a decade so that new project development is quite limited. It should be noted that municipal solid waste and geothermal generation also exist in Thailand, however, their potentials are in research and development phase. So, it is considered that electricity generation in Thailand comprises fossil fuel, wind, solar, small hydro, biomass, and biogas, as shown in Fig. 1. The modeling of each renewable energy resource is described below.

2.1. Wind

The average wind speed in Thailand is moderate to low, typically in the range of 4–6 m/s, while the average wind power density is 4 MW/km^2 [12]. The simplified characteristic of daily wind speed is shown in Fig. 2, with the average speed of 5 m/s. The output power of a wind turbine generator depends on wind speed at specific hub height and turbine characteristics [13]. The output power may be computed by using Eq. (1) but, in this work, a linear

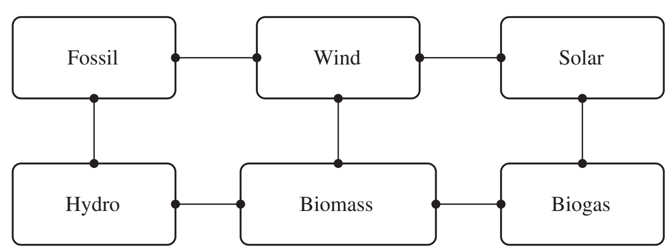

Fig. 1. Resources of electricity generation in Thailand.

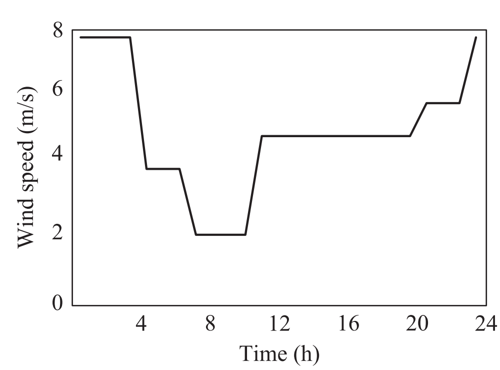

Fig. 2. Simplified characteristic of daily wind speed in Thailand.

power speed curve is assumed as shown in Fig. 3.

$$G_{WI} = \begin{cases} 0 & v < v_I \text{or} v > v_O \\ 0.5\rho_A A_S v^3 C_P & v_I \le v < v_R \\ G_{WI}^R & v_R \le v \le v_O \end{cases} \quad (1)$$

where G_{WI} is output power of wind turbine (W), G_{WI}^R is rated power of wind turbine (W), ρ_A is air density (kg/m^3), A_S is swept area of the rotor (m^2), C_P is the coefficient of performance [12], v is wind speed (m/s), v_I is cut-in wind speed (m/s), v_R is rated wind speed (m/s), v_O is cut-out wind speed (m/s).

2.2. Solar

The solar energy in this work considers only photovoltaic for electricity generation, while solar thermal is neglected. Given that Thailand is near the equator, the annual average solar radiation is up to 18.2 MJ/m^2/d or 5.1 kW h/m^2/d [14]. The simplified characteristic of daily irradiance is shown in Fig. 4, with the insolation period of 12 h per day. The output power of photovoltaic panel depends on solar radiation and inclined surface of PV module and can be stated as shown in Eq. (2)

$$G_{PV} = \eta_I \eta_C I A_P \quad (2)$$

where G_{PV} is output power of *PV* panel (W), η_I is inverter efficiency, η_C is cell efficiency, I is solar irradiance (W/m^2), A_P is panel area (m^2).

2.3. Small hydro

The definition of hydro power depends on generating capacity. Normally, large-scale hydro power is excluded from renewable generation. Micro and Pico hydropower are ignored given that their capacities are simply too small. Thus, small hydropower (in the range of 1–25 MW) with run-of-river type is fitted into the definition of renewable generation [15]. As shown in Eq. (3), the output power of small hydro depends primarily on flow rate, and is considerably independent of water head. The output power of small hydro is relatively constant over a day, but may be varied with seasons.

$$G_{SH} = \eta_G \eta_T \rho_W g Q H \quad (3)$$

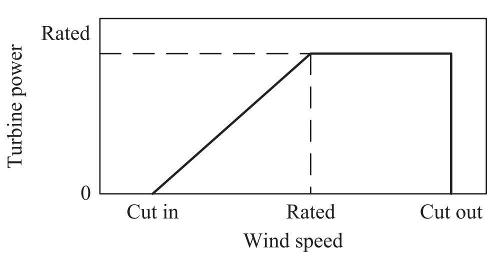

Fig. 3. Linear power speed curve of a wind turbine.

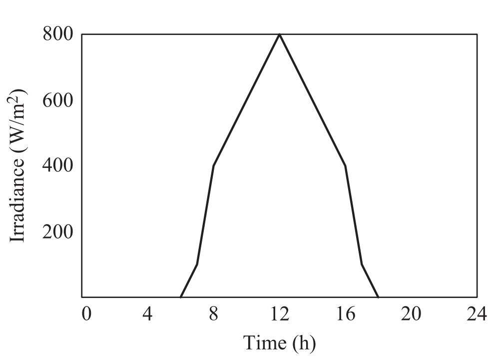

Fig. 4. Simplified characteristic of daily irradiance of Thailand.

where G_{SH} is output power of small hydro unit (W), η_G is generator efficiency, η_T is turbine efficiency, ρ_W is water density (kg/m^3), g is the gravitational acceleration (9.8066 m/s^2), Q is flow rate (m^3/s), H is water head (m).

2.4. Biomass

Regardless of feedstock or conversion technology, electricity generation simply uses biomass in co-firing or in replacement of fossil fuel in conventional power plant, such as steam-turbine generator. Electricity generation from biomass in Thailand is highly season-dependent because the major resource is agricultural residue and waste. For the sake of simplicity, a direct firing of biomass is assumed so that the output power of biomass unit can be stated in Eq. (4).

$$G_{BM} = \eta_{TH} V F \quad (4)$$

where G_{BM} is output power of biomass unit (W), η_{TH} is thermal efficiency of the plant, V is heating value of fuel (Wh/unit of fuel), F is feed rate (unit of fuel/h). Note that unit of solid fuel is usually ton or kg so that the heating value is then expressed as MJ/ton or MJ/kg which can eventually be converted into unit of electrical energy.

2.5. Biogas

Biogas product is a mixture of methane (CH_4), carbon dioxide (CO_2) and other gases. Biogas yield varies with physical and chemical composition of raw material. In Thailand, the major resources are livestock manure (mainly, pig farms) and industrial wastewater [9,10]. Biogas may be burned directly as fuel gas or burned in engine to generate electricity.

The amount of biogas can be calculated from the amount of feedstock, the moisture content, the dry and organic matters, and the gas rate of substrate [16]. Given the amount of biogas, operation period varies from 10 h/d to 24 h/d [17]. The amount of energy can then be calculated from the amount of biogas, the percentage of methane in biogas (normally 50–70%), and the heating value of methane. In Fig. 5, the simplified characteristic of daily biogas rate is shown by using a typical size of biogas plant in Thailand. The flow rate is approximately 20 m^3/h based on 14-h daily operation. Biogas is usually fed into an internal combustion engine (with prior modification) so that the output power equation in Eq. (5) is similar to that of biomass unit.

$$G_{BG} = \eta_{TH} V F \quad (5)$$

where G_{BG} is output power of biogas unit (W), η_{TH} is thermal efficiency of the plant, V is heating value of fuel (Wh/m^3), F is flow rate of biogas (m^3/h). Similarly, the heating value of biogas is expressed as MJ/m^3 which can be converted into unit of electrical energy.

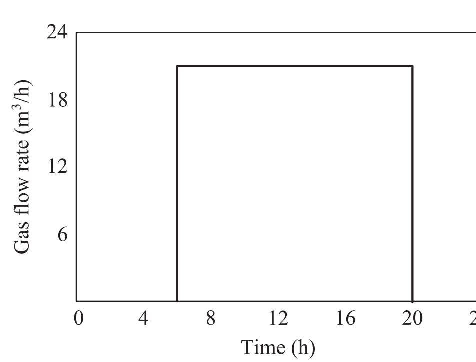

Fig. 5. Simplified characteristic of daily biogas rate in Thailand.

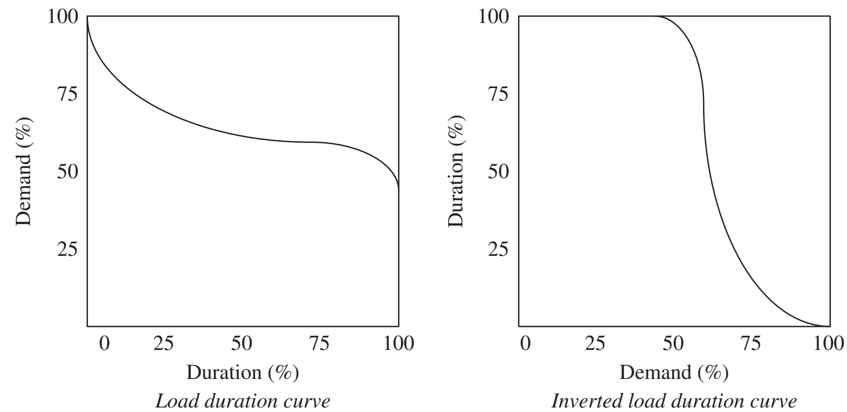

Fig. 6. Load duration curve and inverted load duration curve (normalized form).

3. Generation reliability

In generation planning, there are various criteria in evaluating generation reliability, i.e. the proper amount of generation capacity to serve the power demand [18,19]. Generation reliability may be divided into *adequacy* and *security* [20]. Generation adequacy is considered to be the existence of sufficient capacity to serve the power demand, while generation security is the ability to withstand certain disturbances. Generation reserve margin seems to be the most intuitive and easily criterion. The reserve margin (capacity) is the generation capacity exceeding the peak demand. By considering the loss of largest unit, the reserve margin must also add the size of the largest unit to the reserve capacity. The risk of generation capacity deficit may be defined as the probability that the power demand exceeds the capacity in service (which is installed capacity less capacity outage). Alternatively, the capacity deficit can also be defined as the equivalent load (the sum of power demand and outage capacity) exceeds the installed capacity. By far, there are a number of computational methods for generation reliability under the presence of renewable energy resources, such as Monte Carlo simulation [21,22], analytical methods [6], and fuzzy mathematics [8]. The computation procedure of generation reliability is tedious and can be evaluated by using a number of reliability indexes. Consequently, the contribution of generating unit on reliability is subjective and depends on the reliability index being considered.

3.1. Forced outage rate

With respect to the characteristics of thermal power plants, forced outage rate (FOR), as shown in Eq. (6), is defined as the fraction of time that a generating unit is unavailable for service [19]. The service hour (SH) is the time the unit is available for service, while the forced outage hour (FOH) is the time the unit is unavailable. The FOH is computed from the probability of failure (unavailability) and the mean time to repair. The probability of failure is practically replaced by the mean time to failure. Large unit with high FOR generally has significant and negative impact on generation reliability, and vice versa. However, it may not be proper to extend the FOR with renewable energy generation because the characteristics of renewable energy resources are much different from those of conventional plants.

$$\mathrm{FOR} = \mathrm{FOH}/(\mathrm{FOH} + \mathrm{SH}) \tag{6}$$

3.2. Load duration curve

The load profile over a given time period is normally shown by using load duration curve (LDC), obtained by arranging the chronological power demand in descending magnitude. The vertical axis is for power demand and the horizontal axis is for duration of time (e.g. 8760 h/y). If the axes are inverted, it is then called the inverted load duration curve (ILDC). Fig. 6 compares the LDC and ILDC by normalizing both the power demand and the time duration.

The equivalent load is the sum of actual demand and capacity outages (fictitious load) of all generating units using convolution procedure [23] as shown in Eq. (7).

$$F'(EL) = (1-U)F(EL) + U(EL-C) \tag{7}$$

where $F(\bullet)$ is the cumulative distribution, EL is the equivalent load, U is the FOR of unit of interest, C is the capacity of unit of interest.

The equivalent load duration curve (ELDC) can then be obtained by using the ILDC and normalizing the duration of time. The percentage of time at a given load level may be interpreted as a probability of equivalent load.

3.3. Loss of load probability

The most commonly accepted (but complicated) reliability index would be the so-called loss of load probability (LOLP) [19,20,24]. Note that, actually, the load is not lost but the generation capacity is deficient. By computing at any given time period, the LOLP quantifies the probability that generation capacity is not sufficient to supply power demand (i.e. capacity shortage). As shown in Eq. (8), the calculation of LOLP involves the convolution of the probability of unit availability. The availability is typically represented by a two-state model [20]. The availability capacity of any unit is zero with the probability equals to the FOR. The availability capacity of any unit is one with the probability equals to 1-FOR. Typically, the LOLP is computed on an hourly basis and is in the range of 0.1–1.0 d/y [19].

$$\mathrm{LOLP} = \textstyle\sum_k (prob(C = C_k) x prob(D > C_k)) \tag{8}$$

where C is generation capacity in service, D is power demand, k is index of discretized capacity available in generation system.

3.4. Effective load carrying capability

Capacity credit was proposed to determine the contribution of generating unit on supply adequacy. There are several definitions and methods to compute capacity credit [25]. The most well-known definition would be the effective load carrying capability (ELCC) [26], while firm capacity [27] and guaranteed capacity [8] were introduced recently. Capacity credit is computed by using statistical methods and depends on a set of data so that the result may change over time. Hence, the actual contribution of a

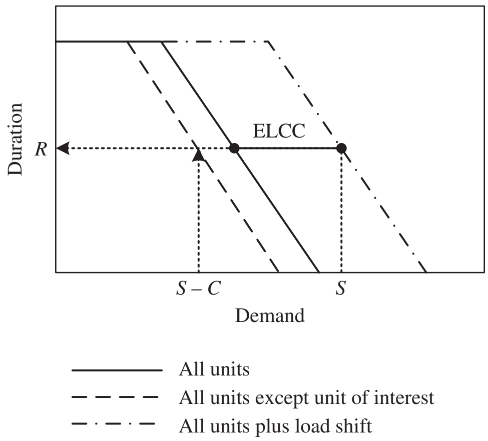

Fig. 7. Illustration of Effective Load Carrying Capability.

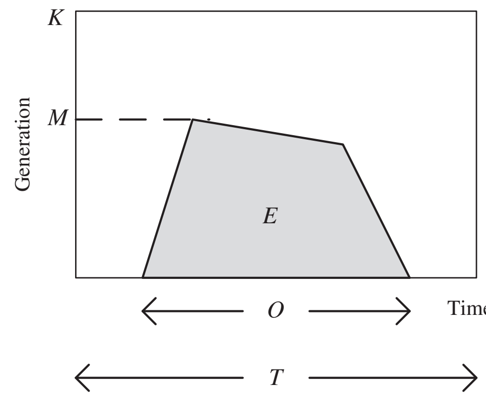

Fig. 8. Generation profile of renewable energy unit.

generating unit on a particular period of time may deviate significantly.

It is practically impossible to validate a capacity credit of a generating unit because the definitions are expressed as a comparative or relative term, i.e. it is not individual property of a generating unit but depends on generation system at a given point in time. Although the value of capacity credit is time dependent, but it can effectively indicate how a generating unit affects the generation reliability.

In this work, the ELCC is proposed to evaluate the contribution of either thermal unit or renewable unit on generation reliability. The computational concept of the ELCC can be visualized by using the ILDC as shown in Fig. 7. Suppose the capacity of all units (system capacity) is S and the capacity of unit of interest is C. The solid line illustrates the ELDC of all units, while the dash line illustrates the ELDC of all units except unit of interest. By projecting from the system capacity less the capacity of unit of interest (S–C), the probability that the equivalent load exceeds the generation capacity of all units except unit of interest is R, which can be considered as reliability level or risk of capacity deficit. When the unit of interest is added to the system, the reliability level would increase and the risk of capacity deficit would decrease so that the system could supply more load. The ELCC of the unit of interest is thus defined as the largest (peak) load shift, i.e. to be added to the existing system without altering the reliability level. Therefore, the contribution of unit of interest on generation reliability can be determined from the ELCC, which can be seen from Fig. 7 that the ELCC is less than the capacity of unit of interest.

4. Solution method

First, load data is required for producing the LDC. Then, generation data of both conventional and renewable units, by means of generation capacity and FOR, are collected to produce the ELDC and compute reliability index. In the absence of FOR information for renewable unit, it is proposed that the equivalent forced outage rate (EFOR) shall be substituted. Based on the generation profile in Fig. 8, the EFOR of renewable energy unit can be computed as shown in Eq. (9).

$$\mathrm{EFOR} = 1-\left(E/T\right)/K = 1-CF \tag{9}$$

where E is energy generation, T is time horizon (e.g. 24 h/d), K is installed capacity, CF is plant or capacity factor (CF). Note that, in Fig. 8, the operating duration (O) of renewable unit is less than the time horizon and the maximum power (M) of renewable unit is also less than the installed capacity. It can be observed that the lower CF, the higher EFOR. For instance, wind and PV units (low CF) would have higher EFOR than that of biomass unit (high CF).

Next, reliability index is computed in order to determine generation reliability level. Finally, the contribution on generation reliability of either conventional unit or renewable unit can be evaluated by using the concept of capacity credit. As mentioned earlier, this work considers the LOLP as the reliability index and the ELCC as the reliability contribution.

To investigate the impact of renewable energy generation on reliability; it is needed to set up two generation systems, one with only conventional capacity and another with both conventional and renewable capacities. The simulation steps are as follows:

- Compare the LOLPs of both generation systems, given that system capacity and load profile are identical.
- Observe change of the LOLPs after varying the penetration levels of renewable capacity.
- Observe change of the LOLPs after varying the penetration levels of renewable capacity and removing conventional capacity in such a way that the system capacity remains constant.

When renewable capacity exists, it is required to determine the ELCC of each renewable energy resource to evaluate reliability contribution. The ELCC is dependent of reserve capacity so that various loading conditions should be assumed.

5. Results and discussion

5.1. Test system

A small-scale generation system comprises two conventional units and five renewable units. They are 750-MW thermal (coal-fired) unit, 250-MW gas-turbine unit, 5-MW wind-turbine unit, 10-MW PV unit, 15-MW hydro unit, 210-MW biomass unit, and 10-MW biogas unit. As a result, the sum of renewable capacities is 250 MW, which is equals to generation capacity of the gas turbine. Note that the generation capacity of each unit was scaled down from the generation capacity portfolio of Thailand. Generation characteristics are taken from the actual data available from the Electricity Generating Authority of Thailand and the Energy Policy and Planning Office, Ministry of Energy.

The load duration curve is assumed to be linearly downward as shown in Fig. 9. The peak demand is 800 MW. The growth of load is assumed in such a way that the load factor is constant.

Numerical simulations were divided into 2 cases with the system capacity of 1000 MW. The reserve margin of both cases is 20%. Case I assumes that the generation system has only two

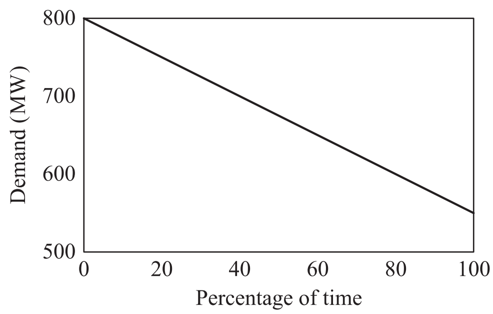

Fig. 9. Load duration curve of the test system.

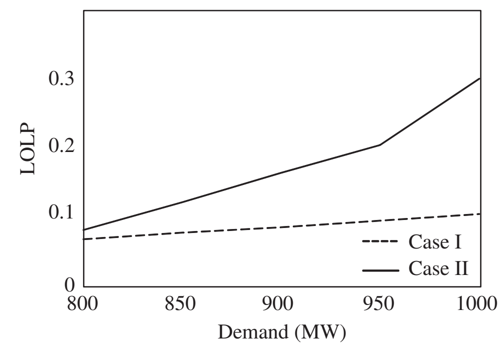

Fig. 10. Comparison of LOLPs under various loading conditions.

Table 2
FOR and EFOR of generating units based on daily generation data in Thailand.

Plant	Capacity (kW)	Max. power (kW)	Operation (h/d)	Energy (kW h/d)	CF	FOR/ EFOR
Thermal						0.060
Gas turbine						0.050
Wind	600	228	21	1,843.32	0.128	0.872
PV	34	27	14	183.60	0.225	0.775
Small hydro						0.020
Biomass	600	470	24	11,280.00	0.783	0.217
Biogas	37	23	14	318.73	0.359	0.641

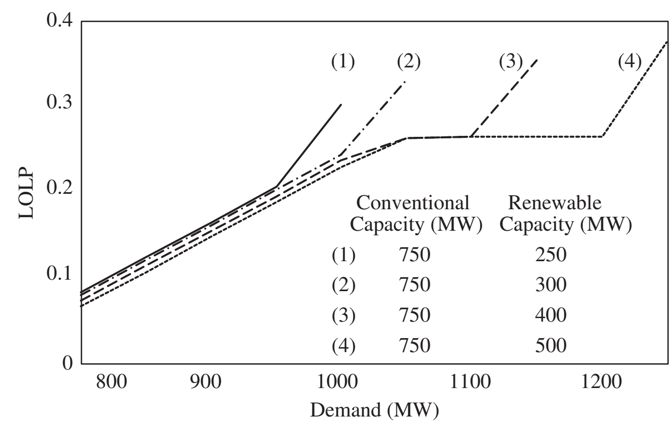

Fig. 11. Comparison of LOLPs under various penetration levels of renewable energy resources.

conventional units which are 750-MW thermal (coal-fired) unit and 250-MW gas-turbine unit. Case II assumes that the gas-turbine unit is replaced by five renewable units. Those are 5-MW wind-turbine unit, 10-MW PV unit, 15-MW hydro unit, 210-MW biomass unit, and 10-MW biogas unit. As a result, renewable capacity in Case II is 25% of the system capacity.

5.2. Reliability evaluation

Based on the daily generation data and generation characteristics of both conventional and renewable units in Thailand, the FOR and EFOR are shown in Table 2. The FORs of thermal, gas-turbine, and small hydro plants were simply taken from typical data. The EFORs of wind-turbine and PV units are high due to their intermittent nature, while the EFOR of biogas unit is relatively high due to gas availability. On the contrary, the EFOR of biomass unit is quite low under the assumption that fuel supply is abundant.

The LOLPs of both cases are compared in Fig. 10. It can be seen that the LOLPs of Case II are always higher than those of Case I, meaning that Case II is less reliable than Case I. As a result, the presence of renewable energy resources has negative impact on generation reliability. This conclusion is intuitive because the EFORs of the renewable units are much higher than the FORs of the conventional units. When the load is growing, the LOLP of Case I is slightly higher, while the LOLP of Case II is spiking. This implies that renewable energy resources would have a severe impact when the generation reserve is low, and vice versa.

To illustrate the impact of penetration levels of renewable energy resources, Case II was modified by keeping the 750-MW thermal unit but increasing the renewable capacity from 250 MW to be 300 MW, 400 MW, and 500 MW. The system capacity was varied from 1000 MW to be 1050 MW, 1150 MW, and 1250 MW so that the renewable capacity accounts for 20–40% of the system capacity accordingly. Note that the generation capacity of each renewable unit was adjusted proportionally. If the generation reserve were neglected, the generation system could serve the peak demand up to 1250 MW.

It is shown in Fig. 11 that the LOLP varies directly with the peak demand but the relationship is nonlinear. It is noticeable that when the peak demand is more than 1000 MW and the renewable capacity is either 400 MW or 500 MW, the LOLP was constant over a certain range of load because the step size of load is less than the capacity outage state. When the peak demand reaches the system capacity, the LOLP is increasing rapidly. By adding more capacity into the generation system, the generation reliability would be better (lower LOLP), regardless of adding conventional or renewable capacity.

Then, it is assumed that the increasing capacity of renewable energy resource should be matched by removing the conventional capacity so that the system capacity remains unchanged. In so doing, the renewable capacity was increased from 250 MW to 500 MW and the conventional capacity was decreased from 750 MW to 500 MW so that the system capacity is constant at 1000 MW. As a result, the renewable capacity was increased from 25% to 50% of the system capacity. Again, the generation capacity of each renewable plant was adjusted proportionally.

When the renewable capacity has higher penetration into the generation system and keeping the system capacity constant, it is shown in Fig. 12 that the generation reliability drops dramatically. The difference in LOLPs at various penetration levels is so obvious when the generation reserve is high (e.g. at 800-MW peak demand). Thus, it must be careful when the renewable capacity has higher proportion in generation capacity. The relationship between the generation reliability (in terms of LOLP) and the penetration level is signified in Fig. 13. Given the desirable level of reliability, the maximum penetration of renewable energy resources may be determined accordingly. For instance, if the

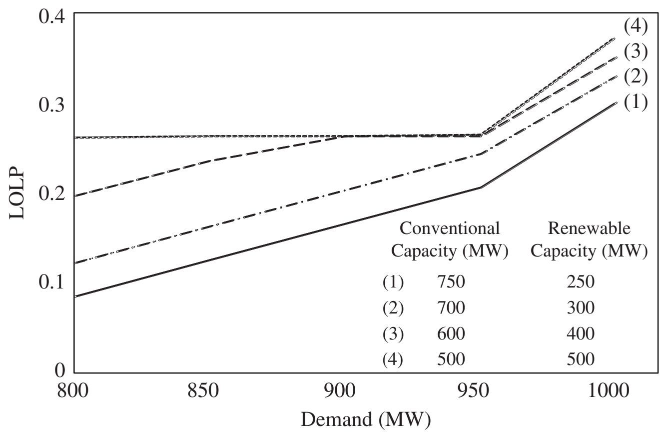

Fig. 12. Comparison of LOLPs under various penetration levels of renewable energy resources with reduction of conventional resource.

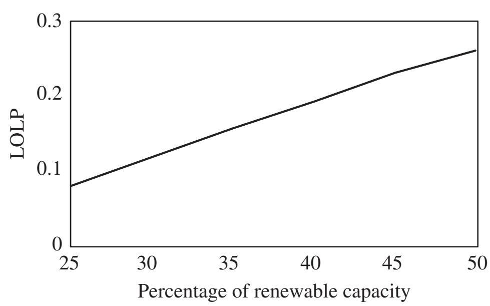

Fig. 13. Impact of penetration level of renewable energy resources on LOLP.

Table 3
ELCC of generating units given three loading conditions (unit: percent of capacity).

Plant	Capacity (MW)	Peak load (MW)		
		800	900	1000
Gas turbine	250	95.67	97.89	100.00
Wind	5	12.88	12.82	12.80
PV	10	22.49	22.47	22.55
Small hydro	15	98.01	97.99	98.25
Biomass	210	49.52	84.01	97.20
Biogas	10	35.85	35.95	35.95
Renewable*	250	73.83	81.39	100.00

* All renewable units are considered all together.

LOLP is bounded at 0.2, the maximum capacity of renewable energy resources would be up to 40% of the system capacity.

Next, the ELCC of each generating unit is evaluated and the result is shown in Table 3. The thermal unit is considered as a standing unit (always exist) of the generation system so that its ELCC was not computed. But, if the ELCC of the thermal unit were needed, the value would be 100% meaning that every unit of capacity contributes to generation reliability.

Refer to Case I, there are only thermal and gas-turbine units. It was found that the ELCC of the gas-turbine unit is almost equal to its capacity. Thus, it may be able to state that almost every unit of capacity is essential for maintaining generation reliability. When the peak demand is 1000 MW which is equal to the system capacity, it is clear that the ELCC of the gas-turbine unit is 100% (i.e. every unit of capacity must be accounted for).

Refer to Case II, the gas-turbine unit was replaced by a group of five renewable units with the total capacity of 250 MW. The ELCCs of renewable units may be separated into two groups based on capacity. For large unit (biomass), the ELCC is proportional to the peak demand. As the load increases, renewable capacity of large unit becomes more essential for generation reliability. In contrast, the ELCCs of small units (wind, PV, small hydro, and biogas) are relatively constant and independent of loading condition. Empirically, it was found that the ELCC of small unit can be approximated as 1-EFOR. If all five renewable units were considered as an aggregated unit, the ELCC is similar to that of biomass unit, i.e. renewable capacity has more contribution to generation reliability as the load increases. But, the ELCC of the gas-turbine unit is more than the ELCC of 250-MW aggregated renewable unit, compared at the same loading condition. This is due to the fact that the aggregated renewable unit consists of five units so that the renewable capacity is less essential than that of the gas-turbine unit. Hence, it is concluded that the contribution on generation reliability of large renewable unit depends on loading condition, while that of small renewable unit is relatively constant.

6. Conclusion

The modeling of wind, PV, small hydro, biomass, and biogas plants was described for evaluating generation reliability. In the absence of operating characteristics of renewable unit, the EFOR was proposed to be a substitute for the FOR of conventional unit. Generation reliability under the presence of renewable energy resources was evaluated by using the LOLP as reliability index and the ELCC as capacity contribution. It is obvious that the penetration of renewable energy resources would have negative impact on generation reliability. The impact of renewable energy resources on generation reliability depends on generation capacity and loading condition. The contribution of renewable energy resources is important and deserves attention when they replace conventional (fossil-fuelled) resources.

Acknowledgments

The authors gratefully acknowledge financial support from the Graduate School, Chiang Mai University and data support from the Electricity Generating Authority of Thailand.

References

[1] Fischer C, Preonas L. Combining policies for renewable energy: is the whole less than the sum of its parts? International Review of Environmental and Resource Economics 2010;4:51–92.
[2] Electricity Generating Authority of Thailand. Summary of Thailand Power Development Plan 2010–2030 (PDP 2010). Electricity Generating Authority of Thailand; 2010.
[3] Department of Alternative Energy Development and Efficiency (DEDE). The 15 years alternative Energy Developing Plan (2008–2022). Ministry of Energy; 2008.
[4] El-Tamaly HH, El-Baset Mohammed AA. Interconnection photovoltaic/wind system with utility on their reliability using a fuzzy scheme. Renewable Energy 2006;31:2475–91.
[5] Dimitrovski A, Tomsovic K. Impact of wind generation uncertainty on generating capacity adequacy. In: Proceedings of the ninth international conference on probabilistic methods applied to power systems; 2006;1–6.
[6] Voorspools KR, D'haeseleer WD. An analytical formula for the capacity credit of wind power. Renewable Energy 2006;31(1):45–54.
[7] Wen J, Zheng Y, Donghan FA. Review on reliability assessment for wind power. Renewable and Sustainable Energy Reviews 2009;13:2485–94.
[8] Amelin M, Söder L. Taking credit: the impact of wind power on supply adequacy-experience from the Sweden market. IEEE Power and Energy Magazine 2010:47–52.
[9] Sawangphol N, Pharino C. Status and outlook for Thailand's low carbon electricity development. Renewable and Sustainable Energy Reviews 2011;15:564–73.
[10] Prasertsan S, Sajjakulnukit B. Biomass and biogas energy in Thailand: potential, opportunity and barriers. Renewable Energy 2006;31:599–610.

[11] Koottatep S, Ompont M, Hwa TJ. Biogas: a GP option for community development. Asian Productivity Organization: e-Books on green productivity, 2005;38-39.
[12] Major S, Commins T, Noppharatana A. Potential of wind power for Thailand: an assessment. Maejo International Journal of Science and Technology 2008;2 (02):255–66.
[13] Capps SB, Hall A, Hughes M. Sensitivity of Southern California wind energy to turbine characteristics. Wind Energy 2011;00:2–28.
[14] Janjai S. Solar energy: a high potential alternative energy for Thailand. In: Proceedings of the 34th congress on science and technology of Thailand, 2008.
[15] Paish O. Small hydro power: technology and current status. Renewable and Sustainable Energy Reviews 2002;6:537–56.
[16] Asam Z, Poulsen TG, Nizami AS, Rafique R, Kiely G, Murphy JD. How can we improve biomethane production per unit of feedstock in biogas plants? Applied Energy 2011;88(6):2013–8.
[17] Sirichan P. Cost analysis of electricity generation from biogas. Mater thesis (Energy Engineering). Chiang Mai University, 2001.
[18] Endrenyi J. Reliability modeling in electric power systems. John Wiley & Sons; 1978.
[19] Stoll HG. Least-cost electric utility planning. New York: John Wiley & Sons; 1989.
[20] Billinton R, Allan RN. Reliability evaluation of power systems. 2nd ed. New York: Plenum Press; 1996.
[21] Billinton R, Chen H. Assessment of risk-based capacity benefit factors associated with wind energy conversion systems. IEEE Transactions on Power Systems 1998;13(3):1191–6.
[22] Vallee F, Lobry J, Deblecker O. System reliability assessment method for wind power integration. IEEE Transactions on Power Systems 2008;23(3):1288–97.
[23] Booth RR. Power system simulation model based on probability analysis. IEEE Transactions on Power Apparatus and Systems PAS-91 1972(1):62–9.
[24] Billinton R, Ringlee RJ, Wood AJ. Power system reliability calculations. Cambridge, MA: The MIT Press; 1973.
[25] Amelin M. Comparison of capacity credit calculation methods for conventional power plants and wind power. IEEE Transactions on Power Systems 2009;24 (2):685–91.
[26] Garver LL. Effective load carrying capability of generating units. IEEE Transactions on Power Apparatus and Systems 1966;85(8):910–9 PAS.
[27] Haslett J, Diesendorf M. The capacity credit of wind power: a theoretical analysis. Solar Energy 1981;26:391–401.